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Unification with Enlarged Kaluza-Klein Dimensions

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Abstract

In minimal theories with extra spatial dimensions at scales μ_0 much lower than the conventional GUT scale, unification can give too-large predictions for $\alpha_3(M_Z)$ given $\alpha_1(M_Z)$ and $\alpha_2(M_Z)$ as empirical input. We systematically study the effects of adding extra states above the compactification scale on running of the gauge couplings and find several simple examples that give unification where all $\alpha_i(M_Z)$ are consistent with low-energy data. We study both the supersymmetric and nonsupersymmetric unification.

Introduction. Theories with extra space-time dimensions arise naturally from superstrings. In particular, extra dimensions may appear at lower scales than the Planck scale, for example at the grand unified scale [1]. One can entertain the possibility that the compactification scale may lie much lower [2–14], even allowing the string scale at 1TeV where one could hope for experimental signatures in the foreseeable future.

For the string scale lying within the TeV region striking signatures are expected depending on the details of a specific model (such as the sizes of the compactified dimensions inside and transverse to the p-branes), ranging from modification of the Newton's law of gravitation at submillimeter distances [14], collider signatures [15], large muon anomalous magnetic moment [16], deviations of electroweak observables [17] and other phenomena [18].

Such theories with compactification scale lower than the usual GUT scale of 10^{16} GeV also strongly impact effects that are associated with scales higher than the weak scale such as proton decay, neutrino masses, flavor changing neutral currents, etc.

If one believes in gauge coupling unification, one can naturally ask how well such couplings unify. Once the gauge couplings cross the compactification scale their running changes on a p-brane for $p > 3$ from logarithmic to power-law [19]. In fact, at energies above the compactification scale μ_0 we can think of an effective higher dimensional theory. For example, one can show that in the case with one $\mathcal{N} = 2$ Higgs hypermultiplet above μ_0 [6] the beta functions in extra dimensions were such that the couplings still approximately unify albeit at the scale very near the compactification scale, because of the power-law running in extra dimensions. The unification is only approximate: given $\alpha_{1,2}(M_Z)$ the prediction for $\alpha_3(M_Z)$ depends on the number of extra dimensions and the compactification scale, but it is typically much higher than the experimental value as soon as the compactification scale is lowered below 10^{16} GeV. For example, for one extra dimension, $\alpha_3(M_Z) \approx 0.13$ at $\mu_0 = 10^{14}$ GeV and goes up to $\alpha_3(M_Z) \approx 0.16$ at $\mu_0 = 10^5$ GeV. Their analysis was further refined at the two-loop level in [12], where it was shown that $\alpha_3(M_Z)$ was further increased. As we will show the situation is even worse in the minimal scenario with two Higgs hypermultiplets above μ_0[1]

One can adopt two attitudes to this situation. The first is simply to abandon unification. After all, $SU(5)$ or $SO(10)$ at scales lower than 10^{16}GeV would simply be disastrous for the proton decay rate. Indeed proton decay is a delicate issue for these enlarged Kaluza-Klein dimensional theories.

But the second more constructive attitude is to try to fix unification with conventional means like adding extra states or scales, while disallowing proton decay on symmetry grounds. Unification into groups like $SU(3)^3$ or Pati-Salam, would avoid proton decay. Other solutions to avoid proton decay that merit further investigation include compactification defined on a Z_2 orbifold, where interactions that lead to proton decay vanish at the orbifold fixed points [6] or gauging and breaking an additional U(1) symmetry on a distant brane [4,7,9].

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[1]We call "minimal" the scenario where each Higgs supermultiplet has its own tower of Kaluza-Klein states, which above μ_0 means two $\mathcal{N} = 2$ hypermultiplets. However, depending on the details of the theory, one can allow for 0,1 or 2 Higgs hypermultiplets and we discuss all scenarios later in the text.

In this paper we assume that the proton decay problem is dealt in some satisfactory manner and we concentrate on the issue of precise gauge unification. We systematically study for which additional field representations unification can be achieved. We assume that extra representations appear at the compactification scale μ_0. We do not add any additional states at M_Z. For the usual case without any extra dimensions couplings do unify in the MSSM to a high degree [20], with the predicted strong coupling value $\alpha_3(M_Z) \approx 0.126$ somewhat higher than the world average $\alpha_3(M_Z) = 0.119 \pm 0.002$. The non-supersymmetric running with extra low lying states has been extensively studied since the early days [21]. One can also include extra matter at some new intermediate scale but we do not consider this possibility in this paper.

We study first the supersymmetric case and search minimal $SU(3) \times SU(2) \times U(1)$ irreducible representations (minimal in the sense that they are contained in (broken) irreducible representations of $SU(5)$ up to dimension **75**). We find several simple representations which predict $\alpha_3(M_Z)$ within experimental limits. Since we are giving up the proton decay constraints and we are adding extra states, it is well justified to ask what happens in the nonsupersymmetric case as well. This case is taken up before we formulate our conclusions.

Supersymmetric Unification. First we derive a simple condition on the beta functions at one-loop level that such extra states must satisfy. We then among those candidates, run the full two-loop analysis similar to Ref. [12].

The evolution equations are

$$\alpha_i^{-1}(M_z) = \alpha_i^{-1}(\mu) + \frac{b_i}{2\pi} \ln\left[\frac{\mu}{M_z}\right], \; M_Z < \mu < \mu_0 \; , \tag{1}$$

below the compactification scale μ_0. Above μ_0 in a theory with $4+\delta$ dimensions we have [2]

$$\alpha_i^{-1}(\mu_0) = \alpha_i^{-1}(\mu) + \frac{(b_i - \tilde{b}_i)}{2\pi} \ln\left[\frac{\mu}{\mu_0}\right] + \frac{\tilde{b}_i X_\delta}{2\pi\delta}\left[\left(\frac{\mu}{\mu_0}\right)^\delta - 1\right], \; \mu_0 < \mu \; , \tag{2}$$

where $b_i = (33/5, 1, -3)$ are the MSSM beta functions, $\tilde{b}_i$ are the beta functions corresponding to the excited Kaluza-Klein states and $X_\delta = \frac{\pi^{\frac{\delta}{2}}}{\Gamma(1+\frac{\delta}{2})}$.

1. Case with two Higgs hypermultiplets. In the scenario where both MSSM Higgses have their corresponding massive Kaluza-Klein towers

$$\tilde{b}_i^{min} = (6/5, -2, -6) + \eta(4, 4, 4) \tag{3}$$

come from contributions from excited Kaluza-Klein states of the standard model fields, including the gauge bosons, Higgs doublets and η chiral generations with $\eta = 0-3$. Allowing

[2] This one-loop equation is actually an approximation to an analytical expression that involves an integral over a Jacobi theta function [6]. However, as shown in [12], which analysis we follow later, this approximation does not affect the two-loop results for low number of extra dimensions ($d = 1-3$) that we consider here.

for $\eta \neq 3$ means that we allow also some generations to have no excited states. One may as well consider the possibility that some of the other standard model states have no Kaluza-Klein excitations. Unification with only $SU(3) \times U(1)$ or $SU(2) \times U(1)$ or just $U(1)$ in the bulk was considered in [13]. We will later consider also the possibility of putting different number of Higgs doublet hypermultiplets.

The procedure is as follows. We will consider the addition of extra states above μ_0 which will change the beta functions to

$$\tilde{b}_i = \tilde{b}_i^{min} + \Delta\tilde{b}_i \ . \tag{4}$$

We proceed by first considering the one-loop part to find an analytic condition on $\Delta\tilde{b}_i$. For the candidates that most closely satisfy the approximate one-loop condition we do the two-loop analysis to find the predictions for $\alpha_3(M_z)$.

Now we require unification at a scale $\Lambda > \mu_0$. Combining equations (1) and (2) and eliminating $\alpha^{-1}(\Lambda)$ we get at one-loop

$$\alpha_i^{-1}(M_z) - \alpha_j^{-1}(M_z) = \frac{(b_i - b_j)}{2\pi}\left\{ \ln\frac{\Lambda}{M_z} - B_{ij}\ln\frac{\Lambda}{\mu_0} + B_{ij}\frac{X_\delta}{\delta}\left[\left(\frac{\Lambda}{\mu_0}\right)^\delta - 1\right]\right\} \ , \tag{5}$$

where

$$B_{ij} \equiv \frac{\tilde{b}_i - \tilde{b}_j}{b_i - b_j} \ . \tag{6}$$

Notice that this formula actually tells us that the couplings would unify to the precision of the MSSM if B_{ij} were not dependent on i and j, so that the curly bracket on the rhs would be a constant with the size of order $\ln\frac{10^{16}\mathrm{GeV}}{M_Z}$. Thus as a first approximation of unification we may consider the condition

$$\frac{B_{12}}{B_{13}} = \frac{B_{13}}{B_{23}} = \frac{B_{12}}{B_{23}} = 1 \ . \tag{7}$$

For the minimal case (3) we have

$$\frac{B_{12}^{min}}{B_{13}^{min}} = 0.76 \ , \frac{B_{13}^{min}}{B_{23}^{min}} = 0.75 \ , \frac{B_{12}^{min}}{B_{23}^{min}} = 0.57 \ , \tag{8}$$

which signals non-unification. Indeed, as shown in Table 2, $\alpha_3(M_Z)$ gets *higher* as μ_0 is lowered and is already 0.16 at $\mu_0 = 10^{14}$ GeV.

Let us now assume that we add extra fields above μ_0 so that the beta functions get changed by $\Delta\tilde{b}_i$ as in (4). Applying the condition (7) translates into

$$5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 12 \ , \tag{9}$$

with the right hand side being non-zero signaling the nonunification in the minimal case $\Delta\tilde{b}_i = 0$.

In Table 1, we list all the $SU(3)) \times SU(2) \times U(1)$ states that are contained in the lowest lying $SU(5)$ multiplets (up to **75**) that have the left hand side of the above equation

between -60 and 60. Notice that above μ_0 states are in complete $\mathcal{N}=2$ hypermultiplets which consist of two chiral multiplets, and that in addition we take two hypermultiplets with opposite charges in order to cancel anomalies.

From Table 1 we see that some simple examples of states that perfectly rectify the one-loop gauge unification include

$$\begin{array}{c} (1,1)_{\pm 1} \text{ hypermultiplets [7] ; or} \\ (1,3)_{\pm 2/3} \text{ and } (2,1)_{\pm 1/2} \text{ hypermultiplets ; or} \\ (2,1)_{\pm 3/2} \text{ and } (2,1)_{\pm 1/2} \text{ hypermultiplets ; or} \\ \text{two } (2,3)_{\pm 5/6} \text{ hypermultiplets ; or} \\ (2,3)_{\pm 7/6} \text{ and } (2,3)_{\pm 1/6} \text{ hypermultiplets .} \end{array} \tag{10}$$

One still has to check for consistency conditions such as whether the couplings remain perturbative. We have performed a numerical, two-loop analysis similarly to Ref. [12][3]. for the states with $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3$ equal to or close to 12. The results are shown in Table 3.

From Tables 3a-3d, we note as expected that the combinations in (10) all have $\alpha_3(M_Z)$ within the MSSM value (or even closer to the world average $\alpha_3(M_Z) = 0.119 \pm 0.002$) for basically all values of μ_0 between the TeV scale and 10^{16} GeV. However, for the last two candidates with extra $(2,3)$ multiplets perturbativity breaks down for lower μ_0[4].

In Tables 3e-3f we have also shown predictions for $\alpha_3(M_Z)$ for some states which are close to the condition in (9). Now of course, the prediction for $\alpha_3(M_Z)$ varies with μ_0. We note an interesting property. The states that have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3$ higher than 12 have lower $\alpha_3(M_Z)$ as μ_0 is lowered and can actually have values compatible with experiments down to intermediate scales. In the opposite case, when $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3$ is lower than 12, $\alpha_3(M_Z)$ gets larger with lower μ_0.

One could object to having states at intermediate scales which have exotic quantum numbers. However, such states are easily found in multiplets of grand unified theories, and indeed, in ordinary supersymmetric theories with more mass scales, it is easy to get extra light exotic states [22]. In any case, a complete unification program should have a complete theory, for which one computes the mass spectrum of states and performs the runnings. Analysis such as presented in this paper should be a guiding point in search for a more complete theory.

2. Cases with one or zero Higgs hypermultiplets. Let us also remark on the possibility that above μ_0 one adds or drops the Kaluza-Klein towers of Standard Model states. Of course, dropping or adding complete generations has no effect on unification except on the size of the coupling at the unification scale. The case where some of the gauge

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[3]The two-loop analysis of [12] actually includes only the two-loop evolution below μ_0, and does not include the two-loop power-law behavior.

[4]Note that perturbativity here is actually the requirement that not just the coupling strength be less than 1, but the product of the inverse coupling strength and the number of KK states (running in the loops).

bosons are left out was studied in [13]. If we assume that there is only one Higgs $\mathcal{N}=2$ hypermultiplet above μ_0 in which case [6]

$$\tilde{b}_i^{min,1higgshm} = (3/5,-3,-6)+\eta(4,4,4) \tag{11}$$

and the unification condition corresponding to (9) is

$$5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 3\ . \tag{12}$$

For this case we have

$$\frac{B_{12}^{min}}{B_{13}^{min}} = 0.94\ ,\ \frac{B_{13}^{min}}{B_{23}^{min}} = 0.92\ ,\ \frac{B_{12}^{min}}{B_{23}^{min}} = 0.86\ , \tag{13}$$

which signals approximate unification [6]. However as noted in [11–13], the approximate unification translates into $\alpha_3(M_Z)$ as high as $0.116-0.117$ for lower values of μ_0. Notice that again this is the same phenomenon as described above, that when the $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3$ is less than 3, $\alpha_3(M_Z)$ grows as μ_0 is lowered.

From Table 1, we see that since the combination $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3$ can only change by ± 6 for complete pairs of hypermultiplets we can not find any extra states that will unify the couplings as MSSM. However, as shown in Table 3h, the extra hypermultiplet pair $(2,3)_{\pm 5/6}$ has $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 6$ and can have acceptable $\alpha_3(M_Z)$ for μ_0 down to intermediate scales.

Finally, one can also consider the case where the MSSM Higgs doublets have no Kaluza-Klein towers. In this case the beta functions in (3) change to

$$\tilde{b}_i^{min,0higgshm} = (0,-4,-6)+\eta(4,4,4) \tag{14}$$

and the unification condition corresponding to (9) is

$$5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = -6\ . \tag{15}$$

In contrast to the minimal case (3) (see also Table 2) here we note that with no extra states the prediction for $\alpha_3(M_Z)$ is *lower* as μ_0 goes down, since now the no-extra-state condition has $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 0$ which is *higher* than condition (15), in accordance with the phenomenon described above. We find for this case $\alpha_3(M_Z) = 0.119$ around $\mu_0 = 10^{15}$GeV as shown in Table 3i. We see from Table 1, that, again, it is easy to find simple extensions for which unification is guaranteed for all scales μ_0. For example Table 3j lists the predictions for $\alpha_3(M_Z)$ when $(1,1)_{\pm 1} + (2,1)_{\pm 1/2}$ hypermultiplets are added.

Nonsupersymmetric Unification. As we saw in the supersymmetric case, unification with extra dimensions at lower scales requires extra states at intermediate scales. Also one needs to get rid of the proton decay either by a non-$SU(5)$ unification or some stringy argument. Thus with the introduction of intermediate scales and not taking into account limits from proton decay, one can then ask why not do away with supersymmetry altogether and study nonsupersymmetric unification.

In Ref. [6] it was actually pointed out that nonsupersymmetric unification is indeed possible with extra dimensions if one adds extra states at μ_0. In this Section we study this

issue more systematically. We find that it is very easy to find simple representations which unify the gauge couplings.

The procedure will be somewhat different than in the supersymmetric case, since the Standard Model does not unify and one cannot use equations (7). Here we study unification only at one-loop. Eliminating $\alpha^{-1}(\mu_0)$ we get from (1) and (2)

$$\alpha_i^{-1}(M_Z) = \alpha^{-1}(\Lambda) + \frac{b_i}{2\pi}\ln\left[\frac{\Lambda}{M_Z}\right] - \frac{\tilde{b}_i}{2\pi}\left[\ln\left[\frac{\Lambda}{\mu_0}\right] - \frac{X_\delta}{\delta}\left(\left(\frac{\Lambda}{\mu_0}\right)^\delta - 1\right)\right], \tag{16}$$

where we have assumed unification at scale Λ, and $b_i = (41/10, -19/6, -7)$ are the standard model beta functions. Similarly to the supersymmetric case, we assume that the couplings unify with addition of some extra matter at the scale μ_0

$$\tilde{b}_i = \tilde{b}_{SMi}^{min} + \Delta\tilde{b}_i\ , \tag{17}$$

where $\tilde{b}_{SMi}^{min} = (1/10, -41/6, -21/2)$.

The procedure now is as follows. From Table 4, we use the $\Delta\tilde{b}_i$ for all the $SU(3) \times SU(2) \times U(1)$ states (scalars or fermions) that are contained in $SU(5)$ mulitplets up to the representation 75.

Then from the three equations (16) we can find the solutions for $\alpha^{-1}(\Lambda)$, Λ and Λ/μ_0 in the form

$$\alpha^{-1}(\Lambda) = \frac{\begin{vmatrix} \alpha_1^{-1}(M_Z) & b_1 & \tilde{b}_1 \\ \alpha_2^{-1}(M_Z) & b_2 & \tilde{b}_2 \\ \alpha_3^{-1}(M_Z) & b_3 & \tilde{b}_3 \end{vmatrix}}{\det}\ , \tag{18}$$

$$\frac{1}{2\pi}\ln\frac{\Lambda}{M_Z} = \frac{\begin{vmatrix} 1 & \alpha_1^{-1}(M_Z) & \tilde{b}_1 \\ 1 & \alpha_2^{-1}(M_Z) & \tilde{b}_2 \\ 1 & \alpha_3^{-1}(M_Z) & \tilde{b}_3 \end{vmatrix}}{\det}\ , \tag{19}$$

$$-\frac{1}{2\pi}\left[\ln\left[\frac{\Lambda}{\mu_0}\right] - \frac{X_\delta}{\delta}\left(\left(\frac{\Lambda}{\mu_0}\right)^\delta - 1\right)\right] = \frac{\begin{vmatrix} 1 & b_1 & \alpha_1^{-1}(M_Z) \\ 1 & b_2 & \alpha_2^{-1}(M_Z) \\ 1 & b_3 & \alpha_3^{-1}(M_Z) \end{vmatrix}}{\det} \approx \frac{43.01}{\det}\ , \tag{20}$$

where

$$\det = \begin{vmatrix} 1 & b_1 & \tilde{b}_1 \\ 1 & b_2 & \tilde{b}_2 \\ 1 & b_3 & \tilde{b}_3 \end{vmatrix} = -\frac{23}{6}\Delta\tilde{b}_1 + \frac{111}{10}\Delta\tilde{b}_2 - \frac{109}{15}\Delta\tilde{b}_3 + \frac{1}{15}\ . \tag{21}$$

The condition for perturbative unification is $N_{KK}\alpha^{-1}(\Lambda) > 1$, while the requirements $1.0\text{TeV} < \Lambda < M_{Pl}$ and $\Lambda/\mu_0 > 1$ give respectively $0.4 < \frac{1}{2\pi} ln\frac{\Lambda}{M_Z} < 6.2$ and $\det > 0$.

In particular the inequality det > 0 tells us that we need a nontrivial SU(2) quantum number, since in det the factor 1/15 is too small and only $\Delta\tilde{b}_2$ has a positive coefficient. Indeed, if we look at the Table 4, in the last column one can see that there is no unification for any SU(2) singlet states or for most of the SU(2) doublet states. However, once the states do obey the above inequalities, one can always find values for Λ/μ_0 and δ for which unification takes place.

In Table 5 we list the five states with lowest Λ. The first case in Table 5 with one extra fermion $(4,1)_{3/2}$ has a μ_0 which is too close to the weak scale and is ruled out empirically. However, the other states which can have μ_0 in tens of TeVs are perfectly allowable. Other states listed in Table 4 that do have unification at intermediate scales might be relevant for indirect signals, like neutrino masses. The highest Λ found is for an extra fermion $(3,6)_{1/3}$ and it is $\Lambda = 1.3 \times 10^{14}$GeV. Thus we see that there are many possible minimal extensions of the nonsupersymmetric models for which we have an intermediate unification.

Conclusions. Lower mass extra dimensions offer the prospect of experimental tests such as submillimeter modification of gravity, missing energy in collider experiments, and departures from the Standard Model, in the foreseeable future.

We have shown that with enlarged extra dimensions, unification of the gauge couplings can be maintained in the supersymmetric case by including certain extra states which have been identified by examining systematically all of the $SU(3) \times SU(2) \times U(1)$ representations that are contained in $SU(5)$ irreducible representations up to the **75**. In fact, the unification can be even more accurate than in the MSSM where the value of $\alpha_3(M_Z)$ is slightly high ($\alpha_3(M_Z) \simeq 0.126$) compared to the data ($\alpha_3(M_Z) = 0.119 \pm 0.002$).

Similarly "perfect" unification has been demonstrated in the non-supersymmetric case. After all, since the gauge hierarchy has been itself ameliorated by the enlargement of the extra dimensions, the motivation for supersymmetry has been correspondingly weakened. Thus, the non-SUSY possibility becomes of more interest.

In our opinion, the Achilles heel of this whole approach lies in the subtle question of the proton stability. On one hand this could of course be cured by a suitable choice of a unification group. On the other hand, the mechanisms that avoid proton decay proposed in the literature, while plausible, certainly merit further investigation for their consistency.

With that one caveat, we feel that the idea of the enlarged Kaluza-Klein dimensions is a very exciting one, particularly as it inspires new insights into old theoretical prejudices.

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Note added: After completion of this paper, an article [23] has been brought to our attention, which has some similarity to the part of our work in the supersymmetric case.

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$SU(2)\times SU(3)_{Y/2}$ state	$\Delta\tilde{b}_1$	$\Delta\tilde{b}_2$	$\Delta\tilde{b}_3$	$5\Delta\tilde{b}_1-12\Delta\tilde{b}_2+7\Delta\tilde{b}_3$
$(3,1)_1+(3,1)_{-1}$	36/5	8	0	-60
$(3,3)_{4/3}+(3,\bar{3})_{-4/3}$	192/5	24	6	-54
$(3,1)_0$	0	4	0	-48
$(2,3)_{1/6}+(2,\bar{3})_{-1/6}$	2/5	6	4	-42
$(2,1)_{1/2}+(2,1)_{-1/2}$	6/5	2	0	-18
$(2,6)_{1/6}+(2,\bar{6})_{-1/6}$	4/5	12	20	0
$(2,3)_{5/6}+(2,\bar{3})_{-5/6}$	10	6	4	6
$(1,1)_1+(1,1)_{-1}$	12/5	0	0	12
$(1,3)_{1/3}+(1,\bar{3})_{-1/3}$	4/5	0	2	18
$(2,8)_{1/2}+(2,8)_{-1/2}$	48/5	16	24	24
$(1,3)_{2/3}+(1,\bar{3})_{-2/3}$	16/5	0	2	30
$(2,1)_{3/2}+(2,1)_{-3/2}$	54/5	2	0	30
$(1,8)_0$	0	0	6	42
$(1,1)_2+(1,1)_{-2}$	48/5	0	0	48
$(2,3)_{7/6}+(2,\bar{3})_{-7/6}$	98/5	6	4	54

Table 1: Extra hypermultiplets for which the combination of beta functions $5\Delta\tilde{b}_1-12\Delta\tilde{b}_2+7\Delta\tilde{b}_3$ is between -60 and 60.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.4	2.13e+16	1.43e+16	0.1284	0.0428
1	0.8	1.15e+16	5.16e+15	0.1331	0.0420
1	1.2	4.08e+15	1.23e+15	0.1420	0.0407
1	1.6	7.84e+14	1.58e+14	0.1592	0.0389
1	2.0	6.00e+13	8.13e+12	0.1970	0.0363
1	2.4	1.19e+14	1.09e+11	0.3142	0.0330
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.8	1.33e+15	5.97e+14	0.1538	0.0395
2	1.2	7.09e+12	2.14e+12	0.2492	0.0344
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	5.84e+15	3.91e+15	0.1392	0.0412
3	0.8	1.54e+13	6.93e+12	0.2286	0.0351

Table 2: Predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$ in the supersymmetric model with enlarged Kaluza-Klein dimensions with two KK towers for MSSM Higgs and no extra states. Inputs are the number of extra dimensions δ and $\rho\equiv\ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta=0$).

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.8	5.54e+15	2.49e+15	0.1250	0.0417
1	1.6	4.84e+13	9.78e+12	0.1228	0.0379
1	2.4	4.71e+08	4.27e+07	0.1179	0.0310
1	2.6	4.00e+06	2.97e+05	0.1158	0.0289
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.8	1.22e+14	5.48e+13	0.1235	0.0386
2	1.4	2.38e+06	5.86e+05	0.1161	0.0286
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.6	4.25e+13	2.33e+13	0.1231	0.0379
3	1.0	1.40e+05	5.15e+04	0.1151	0.0275

Table 3a: Extra pair of $(1,1)_{\pm 1}$ multiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 12$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	1.2	8.96e+14	2.70e+14	0.1241	0.0420
1	2.2	2.25e+10	2.49e+09	0.1195	0.0387
1	2.6	4.00e+06	2.97e+05	0.1158	0.0362
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.8	1.22e+14	5.48e+13	0.1235	0.0414
2	1.2	1.13e+10	3.39e+09	0.1196	0.0385
2	1.4	2.38e+06	5.86e+05	0.1161	0.0362
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.8	4.47e+10	2.01e+10	0.1203	0.0389
3	1.0	1.40e+05	5.15e+04	0.1151	0.0355

Table 3b: Extra pairs of $(1,3)_{\pm 2/3} + (2,1)_{\pm 1/2}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 12$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.8	1.04e+15	4.66e+14	0.1243	0.0430
1	1.2	2.72e+13	8.19e+12	0.1227	0.0428
1	1.6	7.98e+10	1.61e+10	0.1202	0.0424
1	1.8	1.38e+09	2.28e+08	0.1185	0.0421
1	2.0	8.87e+06	1.20e+06	0.1164	0.0417
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.4	1.35e+15	9.03e+14	0.1246	0.0431
2	1.0	3.13e+08	1.15e+08	0.1183	0.0420
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	9.34e+13	6.26e+13	0.1235	0.0429
3	0.6	6.05e+10	3.32e+10	0.1205	0.0424

Table 3c: Extra pairs of $(2,1)_{\pm 3/2} + (2,1)_{\pm 1/2}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 12$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.4	9.12e+15	6.11e+15	0.1254	0.0446
1	0.8	1.04e+15	4.66e+14	0.1243	0.0473
1	1.2	2.72e+13	8.19e+12	0.1227	0.0526
1	1.6	7.98e+12	1.61e+10	0.1202	0.0642
1	2.0	8.87e+06	1.20e+06	0.1164	0.0976
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.6	6.14e+13	3.37e+13	0.1233	0.0514
2	1.0	3.13e+08	1.15e+08	0.1183	0.0814
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.2	4.37e+15	3.57e+15	0.1251	0.0455
3	0.6	6.05e+10	3.32e+10	0.1205	0.0651

Table 3d: Two extra pairs of $(2,3)_{\pm 5/6}$ hypermultiplets (or extra pairs of $(2,3)_{\pm 7/6} + (2,3)_{\pm 1/6}$ hypermultiplets ; they have the same $\Delta\tilde{b}$s) above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 12$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	1.0	5.02e+15	1.85e+15	0.1197	0.0412
1	1.2	2.41e+15	7.26e+14	0.1174	0.0404
1	1.6	2.98e+14	6.01e+13	0.1113	0.0384
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.4	9.83e+15	6.59e+15	0.1221	0.0420
2	0.8	5.79e+14	2.60e+14	0.1136	0.0390
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	3.78e+15	2.53e+15	0.1190	0.0409
3	0.6	2.72e+14	1.49e+14	0.1113	0.0383

Table 3e: Extra pair of $(1,3)_{\pm 1/3}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 18$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	1.0	4.23e+14	1.55e+14	0.1188	0.0446
1	1.2	7.32e+13	2.21e+13	0.1162	0.0452
1	1.6	4.92e+11	9.94e+13	0.1093	0.0470
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.4	2.09e+15	1.40e+15	0.1215	0.0441
2	0.8	2.38e+12	1.07e+12	0.1116	0.0465
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	2.11e+14	1.42e+14	0.1180	0.0449
3	0.6	3.89e+11	2.13e+11	0.1093	0.0472

Table 3f: Extra pairs of $(1,1)_{\pm 1} + (2,3)_{\pm 5/6}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 18$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	1.0	1.24e+15	4.55e+14	0.1299	0.0451
1	2.0	2.29e+10	3.10e+09	0.1460	0.0528
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.8	2.57e+13	1.16e+13	0.1356	0.0477
2	1.2	1.69e+08	5.10e+07	0.1552	0.0573
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	7.38e+14	4.95e+14	0.1309	0.0455
3	0.6	6.64e+12	3.65e+12	0.1377	0.0486

Table 3g: Extra pair of $(2,3)_{\pm 5/6}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 6$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.6	7.04e+15	3.87e+15	0.1240	0.0440
1	1.0	1.03e+15	3.77e+14	0.1216	0.0442
1	1.4	4.43e+13	1.09e+13	0.1180	0.0451
1	1.8	3.11e+04	5.14e+10	0.1128	0.0467
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.4	3.64e+15	2.44e+15	0.1233	0.0439
2	0.8	1.70e+13	7.65e+12	0.1172	0.0455
2	1.0	1.14e+11	4.19e+10	0.1121	0.0471
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	5.94e+14	3.98e+14	0.1212	0.0444
3	0.6	4.06e+12	2.23e+12	0.1158	0.0460

Table 3h: Case with only one Higgs hypermultiplet and extra pair of $(2,3)_{\pm 5/6}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = 6$.

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.6	1.39e+16	7.63e+15	0.1232	0.0418
1	1.0	5.02e+15	1.85e+15	0.1197	0.0399
1	1.4	9.53e+14	2.35e+14	0.1146	0.0372
1	1.6	2.98e+14	6.01e+13	0.1113	0.0356
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.4	9.83e+15	6.59e+15	0.1221	0.0411
2	0.8	5.79e+14	2.60e+14	0.1134	0.0366
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.4	3.78e+15	2.53e+15	0.1190	0.0395
3	0.6	2.72e+14	1.49e+14	0.1113	0.0355

Table 3i: Case with no Higgs hypermultiplets and no extra hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$).

δ	ρ	Λ	μ_0	$\alpha_3(M_Z)$	$\alpha(\Lambda)$
1	0.0	3.00e+16	3.00e+16	0.1260	0.0433
1	0.6	1.03e+16	5.65e+15	0.1253	0.0423
1	1.0	2.49e+15	9.16e+14	0.1246	0.0410
1	1.4	2.46e+14	6.06e+13	0.1235	0.0391
1	1.8	6.37e+12	1.05e+12	0.1219	0.0365
1	2.2	2.25e+10	2.49e+09	0.1195	0.0330
1	2.6	4.00e+06	2.97e+05	0.1158	0.0288
2	0.0	3.00e+16	3.00e+16	0.1260	0.0433
2	0.4	6.34e+15	4.25e+15	0.1252	0.0419
2	0.8	1.22e+14	5.48e+13	0.1235	0.0386
2	1.2	1.13e+10	3.39e+09	0.1196	0.0327
2	1.4	2.38e+06	5.86e+05	0.1161	0.0286
3	0.0	3.00e+16	3.00e+16	0.1260	0.0433
3	0.6	4.25e+13	2.33e+13	0.1231	0.0379
3	0.8	4.47e+10	2.01e+10	0.1203	0.0335
3	1.0	1.40e+05	5.15e+04	0.1151	0.0275

Table 3j: Case with no Higgs hypermultiplets and extra pairs of $(1,1)_{\pm 1} + (2,1)_{\pm 1/2}$ hypermultiplets above μ_0: predictions for $\alpha_3(M_z)$ and $\alpha(\Lambda)$. Inputs are the number of extra dimensions δ and $\rho \equiv \ln(\Lambda/\mu_0)$. Number of chiral generations with Kaluza-Klein towers has been set to zero ($\eta = 0$). The extra states have $5\Delta\tilde{b}_1 - 12\Delta\tilde{b}_2 + 7\Delta\tilde{b}_3 = -6$.

$SU(2)\times SU(3)_{Y/2}$	$\Delta\tilde{b}_1$	$\Delta\tilde{b}_2$	$\Delta\tilde{b}_3$	$\frac{1}{2\pi}\ln(\Lambda/M_Z)$
$(1,1)_1$	1/5	0	0	
$(1,1)_2$	4/5	0	0	
$(1,3)_{-1/3}$	1/15	0	1/6	
$(1,3)_{2/3}$	4/15	0	1/6	
$(1,3)_{-4/3}$	16/15	0	1/6	
$(1,3)_{5/3}$	5/3	0	1/6	
$(1,6)_{1/3}$	2/15	0	5/6	
$(1,6)_{-2/3}$	8/15	0	5/6	
$(1,6)_{-4/3}$	32/15	0	5/6	
$(1,8)_0$	0	0	1/2	
$(1,8)_1$	8/5	0	1/2	
$(1,10)_1$	2	0	5/2	
$(1,15)_{-1/3}$	1/3	0	10/3	
$(1,15')_{-4/3}$	16/3	0	35/6	
$(2,1)_{1/2}$	1/10	1/6	0	
$(2,1)_{-3/2}$	9/10	1/6	0	
$(2,3)_{1/6}$	1/30	1/2	1/3	F(1.53)
$(2,3)_{5/6}$	5/6	1/2	1/3	
$(2,3)_{7/6}$	49/30	1/2	1/3	
$(2,6)_{1/6}$	1/15	1	5/3	
$(2,6)_{5/6}$	5/3	1	5/3	
$(2,6)_{-7/6}$	49/15	1	5/3	
$(2,8)_{-1/2}$	4/5	4/3	2	
$(2,10)_{-1/2}$	1	5/3	5	
$(3,1)_1$	3/5	2/3	0	F(2.09)
$(3,1)_0$	0	1/3	0	F(1.79)
$(3,3)_{-1/3}$	1/5	2	1/2	S(2.32) or F(4.04)
$(3,3)_{2/3}$	4/5	2	1/2	S(1.84) or F(3.81)
$(3,3)_{-4/3}$	16/5	2	1/2	F(1.27)
$(3,6)_{1/3}$	2/5	4	5/2	S(3.22) or F(4.46)
$(3,8)_0$	0	8/3	3/2	S(2.67) or F(4.31)
$(4,1)_{1/2}$	1/5	5/3	0	S(2.20) or F(3.93)
$(4,1)_{3/2}$	9/5	5/3	0	S(0.43) or F(3.07)
$(4,3)_{7/6}$	49/15	5	2/3	S(3.21) or F(4.02)
$(5,1)_2$	4	10/3	0	S(1.95) or F(3.36)

Table 4: Beta functions for extra scalar $SU(3)\times SU(2)\times U(1)$ states that can be found in broken multiplets of $SU(5)$ up to the **75**. All scalars are complex except $(3,1)_0$, $(1,8)_0$ and $(3,8)_0$. Beta functions for corresponding fermion pairs (Dirac fermions) are obtained by multiplying the above scalar functions by 4. Supersymmetric beta functions for supermultiplets with the same quantum numbers are obtained by multiplying the scalar beta functions by 6 (*cf.* Table 1). The last column indicates values for $\frac{1}{2\pi}\ln(\Lambda/M_Z)$ where nonsupersymmetric unification does occur, either with one extra scalar (S) or one fermion pair (F) at μ_0.

Extra state	$\alpha^{-1}(\Lambda)$	Λ	δ	μ_0
S $(4,1)_{3/2}$	50.1	$1.4 \times 10^3 GeV$	1	$1.0 \times 10^2 GeV$
			2	$3.4 \times 10^2 GeV$
			3	$5.4 \times 10^2 GeV$
F $(3,3)_{-4/3}$	31.8	$2.7 \times 10^5 GeV$	1	$3.6 \times 10^4 GeV$
			2	$9.3 \times 10^4 GeV$
			3	$1.3 \times 10^5 GeV$
F $(2,3)_{1/6}$	51.8	$1.4 \times 10^6 GeV$	1	$1.1 \times 10^5 GeV$
			2	$3.5 \times 10^5 GeV$
			3	$5.4 \times 10^5 GeV$
F $(3,1)_0$	51.3	$7.0 \times 10^6 GeV$	1	$6.2 \times 10^5 GeV$
			2	$1.9 \times 10^6 GeV$
			3	$2.9 \times 10^6 GeV$
S $(3,3)_{2/3}$	48.9	$9.6 \times 10^6 GeV$	1	$8.8 \times 10^5 GeV$
			2	$2.7 \times 10^6 GeV$
			3	$4.0 \times 10^6 GeV$

Table 5: States at μ_0 for which couplings unify in extra dimensions.